Wireless Sensor Systems with Energy Harvesting Capabilities for Safety Enhancement in Agricultural Vehicles

A. Bertacchini
Department of Engineering Sciences and Methods
DISMI -University of Modena and Reggio Emilia
Reggio Emilia, Italy
alessandro.bertacchini@unimore.it

L. Larcher
Department of Engineering Sciences and Methods
DISMI -University of Modena and Reggio Emilia
Reggio Emilia, Italy
luca.larcher@unimore.it

***Abstract*—This paper presents an overview of a multi-sensor wireless system applied to agricultural vehicles. The data provided by the different kinds of ad-hoc developed wireless sensors can be used as starting point for the implementation of an automatic system for the active safety enhancement of the vehicles. In order to guarantee a lifetime comparable with the one of the implement or trailer where they are mounted, each sensor has his own energy harvesting system able to gather energy from the vibrations occurring in the environment where the sensor operates.**

Keywords*—*Wireless Sensors, Energy Harvsting, Active Safety Enhancement; Electronics for Agriculture, HW-SW Codesign.

I. INTRODUCTION

Safety enhancement for operators and machineries is a research topics which is gaining interest in a growing number of application fields. For example, huge efforts have been spent to introduce advanced electronic systems for active pre-crash safety of the passengers in automotive, while in agriculture the efforts have been concentrated only in the introduction of passive safety systems like roll-bars.

National and international statistics (e.g. [1]-[2]) confirm continuously that agriculture is an application field with one of the highest percentage of fatalities per year related to the number of employees, but the development of dedicated electronic devices for active and pre-crash safety in this environment has collected lacking in interest. The introduction of this kind of automatic electronic devices is widely motivated by the nature of the fatalities. Most of the accidents, indeed, occur due to human errors typically related to operators that ignores the machinery limits leading to a tractor rollover, or taking shortcuts to saving time (e.g. [3]).

In the last years, the introduction of new enabling technologies allowed to boost the research activities of both academia and industry in the field of safety in agriculture, as demonstrated by the growing number of papers on this topic. Among others, wireless sensor nodes and energy harvesting devices are the two enabling technologies that allowed to overcome the two most limiting factors in the extensive use of electronic systems in agricultural machineries.

The first one is the limited lifetime of the batteries used in classic wireless devices, that is not comparable with the typical lifetime of the trailers or the implements on which they are mounted. The introduction of wireless devices able to gather energy from their working environment allows to significantly extend the lifetime of the devices. The second one is related to the absence of any on board electronic device for the most of the implements and trailers available on the market, with the consequence that they cannot exchange any data with the tractor. The absence of electronic devices on the connected implements or trailers allowed, up to now, to obtain models of the dynamics of the whole machinery and control stability algorithms which are not able to update their input data accordingly with the instantaneous working conditions of the whole machinery. This occurs, of course, because they do not have any input data warning about the presence and the working conditions of connected trailers or implements. For instance, in [4] and [5] the vehicle yaw angle was observed for stability purposes to detect if the vehicle is approaching a dangerous condition detected by the estimation of the physical limit of adhesion between the tires and the road. Similarly, in [6] and [7] the focus was on the critical detection of side-slip issue occurring at non-zero roll angles proposing a very accurate model based on active angle control of the front wheels and estimation of the vehicle dynamics, respectively.

But the behavior of the whole machinery changes drastically if an implement or a trailer is connected to the tractor. At this regard a conceptually very simple information like the automatic identification of what is connected to the tractor, [8], can be very useful. Another key information to detect if a potentially dangerous working condition is approaching in articulated vehicles is the estimation of the relative positioning between tractor and implement/trailer. Several works show that this information can be obtained in several ways. For example, it is possible to exploit post-processing of data collected on the primary vehicle [9], or external infrastructure [10], or expensive sensors [11] using techniques based on odometry or external observers in combination with Kalman filters.

The ad-hoc wireless devices presented in this paper aim to be a possible easy-to-install solution for all the main issues described above. Indeed, they can be used as starting point to implement a more complex electronic system for the active safety enhancement in agricultural vehicles. Adopting the proposed wireless sensor system, when an implement (or trailer) is connected to the tractor, it can be automatically identified, and the stability control algorithm running in the main ECU of the vehicle can instantaneously update the vehicle-related parameters of the dynamics model taking into account, if necessary, also other information (e.g. the relative position between tractor and implement/trailer). This enables the capability to detect hazardous working conditions of the whole machinery, increasing the effectiveness of traditional vehicle stability control algorithms, thus enhancing the active and pre-crash safety.

Interestingly, the use of these devices is not theoretically limited to the case of agricultural vehicles. They can be used in any industrial application where there are articulated systems with more than one degree of freedom using interchangeable tools like robotic arms, manipulator, earth moving vehicles, telehandlers, etc…

As described in the following, the proposed devices have been developed exploiting an hardware-software co-design methodology, combining Ultra-Low Power wireless architecture with smart task management algorithms. Moreover they embed customized energy harvesting systems allowing to obtain perpetual and energy autonomous devices.

The paper is organized as follows. Section II describes the proposed system architecture and some HW-SW co-design considerations. Section III summarizes the implemented task managers used to optimize the power consumption of the proposed wireless devices. Experimental results are shown in Section IV, while Section V concludes the paper.

II. Description of the Proposed System Architecture and HW-SW Co-design Considerations

The real industrial application of a tractor with a connected baler is used as case study in this paper. As shown in Fig. 1, the general system architecture consists of two wireless end-devices (ED1 and ED2) installed on the baler and a Data Manager Device (DMD) installed on the tractor.

The ED1 has been designed to identify univocally the baler providing also its main parameters needed to execute the stability control algorithm running on the main ECU of the tractor. At the same time it has to provide information about the relative position of the baler with respect to the tractor.

The ED2, instead is in charge of two tasks. The first one is the monitoring of the oil temperature inside the gearbox connected to the tractor Power Take-Off (PTO) by means of a drive shaft, which is located in a position where traditional sensors cannot be installed due to dimensional and power supply constraints. The second one is the count of the effective working time of the gearbox that needs of periodical maintenance for the safety of both machinery and operator.

Finally, the DMD has been designed to perform two main tasks: i) it executes the implemented spatial positioning algorithm to detect if a potentially dangerous working

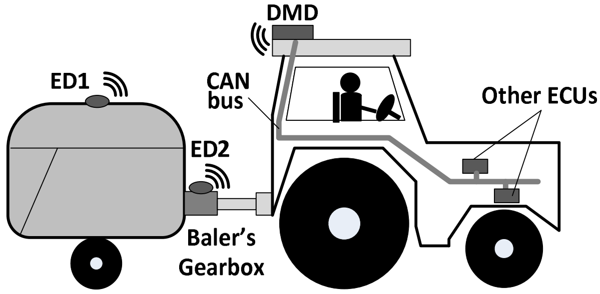

Fig. 1. Conceptual system architecture with DMD (on the tractor) with CAN interface to exchange data with the other ECUs of the vehicle and wireless interface to communicate with the ED1 and ED2 (on the baler). Up to 8 wireless EDs can be simultaneously installed on the whole machinery.

condition is approaching by estimating the relative positioning between tractor and baler; ii) it operates as gateway forwarding the results of its computations and the data received from the EDs to the other ECUs of the tractor.

As mentioned before, all the realized devices have been developed using an HW-SW co-design approach keeping some key features common to all the devices. This allows to reduce the design time of the hardware because the devices have the same main functions (e.g. automatic identification) and differs only for application specific details (e.g. monitoring of different physical parameters). In addition, this allows to simplify the porting of some reusable software modules and the integration of the single devices in a more complex system, improving the overall active safety functionalities of the whole system.

With reference to the considered case study, the EDs installed on the baler have been designed to be as more general purpose as possible. All the realized devices adopt the same ULP microcontroller (i.e. MSP430F2274 16bit RISC CPU from Texas Instruments), which combines very good flexibility in terms of computational performance and inter-chip connectivity for smart sensors interfacing (e.g. SPI, I^2C ports), the same 2.4GHz transceiver (i.e. CC2500 IEEE 802.15.4 compliant low-power device from Texas Instruments), and the same wireless communication protocol to exchange data with the DMD. In addition, they have also the same energy harvesting system able to gather energy from the vibrations occurring on the baler when on duty. Vice versa they have different sensors on board. The ED1 embeds a MEMS inertial sensor (i.e. the LSM303DLHC from STMicroelectronics) with an integrated 3D linear accelerometer and a 3D magnetometer, while ED2 embeds a 3-axial MEMS accelerometer (i.e. LIS3DH from STMicroelectronics), a temperature sensor (i.e. ADT7301 from Analog Devices) and a ULP Real Time Clock (i.e. MCP795W21 from Microchip).

All the mentioned hardware components have been chosen taking into account two main features required by the HW-SW co-design approach used: i) Ultra Low-Power consumption; ii) digital interface with SPI or I^2C connectivity in order to simplify the hardware and the firmware design of the EDs.

For the DMD device, instead, a processor with redundant architecture has been chosen because of the safety critical functions it has to carry out. Its core is an ARM Cortex-R4F processor (i.e. the RM48L952 from Texas Instruments) with these main features: a dual CPU operating in lockstep, a memory with built-in self-test logic for single bit error correction and double bit error detection, and a multiple inter-chip serial interfaces (i.e. UART, SPI, I^2C and embedded CAN controllers).

The DMD operates as communication bridge between the EDs and any other ECUs installed on the tractor (e.g. displays). Of course, it embeds the same 2.4GHz transceiver and implements the same wireless communication protocol used by the EDs. The received data are forwarded to the other electronic devices installed on the tractor by means of a standard CAN communication (i.e. embedded CAN controller with bus access guaranteed by an external SN65HVDA541 CAN transceiver from Texas Instruments, qualified for use in automotive applications).

The DMD embeds also the same MEMS inertial sensor (i.e. the LSM303DLHC from STMicroelectronics) used by ED1 and needed to estimate the relative positioning between tractor and baler.

Due to the modularity of both the hardware functional blocks of the devices and the implemented firmware architecture, additional safety functions can be easily integrated in the system by adding slight modifications to the firmware of the DMD and expanding the implemented wireless sensor network adding other EDs using the same common components of ED1 and ED2 with the only customizations related to the additional parameters of interest to monitor.

A. ED1 – End Device for monitoring of the relative position of the baler with respect to the tractor

The first task of the ED1 is the univocally identification of the implement or trailer on which it is mounted. The ED1 sends periodically a data packet containing both the unique identifier (ID) of the implement/trailer and its mechanical parameters (e.g. physical dimensions, barycenter, weight, maximum load capacity, etc…) required by the main ECU of the tractor to perform the stability control algorithm of the vehicle. All the parameters are specific for the single implement and are set at the programming time of the microcontroller (μC). The data packet is used also as "alive message" to inform the DMD of the ED1's correct operation.

In addition, ED1 measures the pitch and roll angles of the baler by means of its embedded MEMS inertial sensor. These data are used to detect the instantaneous Risk Level Condition (RLC) of the baler. A dangerous working condition for a tractor with a connected baler can occur when: i) the pitch angle of the machinery becomes very large, which drives the machinery close to its brake/acceleration limit; ii) the roll angle of the machinery becomes very large, which may cause machinery side slip; iii) the relative yaw angle between tractor and baler approaches its maximum allowed angle, which can induce the tractor into jackknifing.

RLC have been discretized in 5 steps ranging from *"very low"* to *"very high"* depending on the measured pitch and roll angles and they are used to optimize the power consumption of the ED1. This is very important since no conventional power supply sources are available on the baler and the only available energy sources are the implemented vibrational energy harvesting circuit and the backup rechargeable Li-Ion battery. In particular, when a potentially dangerous working condition is approaching (i.e. the estimated RLC index increases) the ED1 increases accordingly the sampling rate of the sensor for a more frequent update of pitch and roll angles. Vice versa when no potentially dangerous working conditions are present (i.e. low RLC index) the ED1 reduce its calculation rate of the pitch and roll angles of the baler, reducing its power consumption.

The algorithm computing the roll and pitch angles running on the ED1 is based on a Look-Up-Table (LUT) approach which allowed to obtain an energy consumption reduction up to 94% compared to the classical fixed-point calculation with a better precision at the cost of a larger memory occupation [12]. The computational errors introduced by a classic fixed-point approach reduce the overall angle precision, while a LUT approach can benefit from more accurate data that are precompiled in memory, providing a higher angle computational precision. The yaw angle estimation, needed to determine the relative position of the baler, is a very time and power consumption task. Therefore, due to the power consumption constraints of the ED1, it is demanded to the DMD device and the estimated pitch and roll angles are transmitted to the DMD as raw data with no additional computations.

The simplified block diagram of the ED1 is shown in Fig. 2. The energy harvester converts the kinetic energy associated with the vibrations of the baler into useful electrical energy. The collected energy is converted into the electrical form by a commercial piezoelectric PZT transducer (i.e. V22B from MIDE Technology). In order to be an effective power generator, it has to be tuned to match its resonance frequency with the main vibration frequency of implement on which it is mounted (e.g. 112 Hz for the considered baler, see section IV). Unfortunately, due to the very narrowband behavior of the PZT transducers, the tuning is needed for each type of implement.

The AC signal provided by the transducer is rectified and transformed in a stable 3.3VDC output voltage by a commercial LTC3588-1 from Linear Technology. Its output is connected to a simple circuit based on the LTC4070 from Linear Technologies, that implements a power management policy based on the instantaneous power consumption of ED1

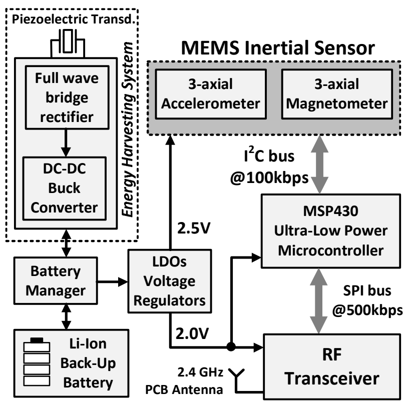

Fig. 2. Simplified block diagram of the implemented ED1

and the instantaneous amount of available harvested energy. In particular, at a given time, if the energy required by the ED1 is larger than the amount of energy harvested, the battery manager drains from the Li-Ion back-up battery the remaining amount of energy needed to supply the node. Vice versa if, at a given time, the harvested energy is higher than the energy required by the ED1, it uses the exceeding energy to recharge the Li-Ion battery. A circuit based on commercial Linear Drop Out (LDO) regulators with ultra-low quiescent current provides the regulated voltages needed for the correct operation of the ED1's components, minimizing its power consumption.

Finally, the interfacing between the inertial sensor and the ED1's ULP microcontroller exploits a I^2C protocol, while the interfacing between the RF transceiver used for the wireless data exchange with the DMD and the ED1's ULP microcontroller exploits a SPI protocol.

B. *ED2 – End Device for measuring oil temperature and effective working time of the gearbox connected to the tractor PTO*

From an hardware point of view, thanks to the HW-SW co-design approach used, the design of the ED2 device takes advantage from the design of the ED1. In particular, it exploits the same energy harvesting system, the same power management circuitry, as well as the same microcontroller and the same RF transceiver. The only hardware modifications concern the introduction of the ULP components needed to perform the two tasks of the device: i) monitoring of the oil temperature inside the gearbox connected to the tractor Power Take-Off (PTO) by means of a drive shaft; ii) count of the effective working time of the gearbox for its programmed maintenance. To do this, it embeds a digital temperature sensor, a Real Time Clock and a 3-axial accelerometer, which is used also to detect the effective working conditions of the baler. All these sensors share the same SPI bus with the RF transceiver. Both the oil temperature and the count of the effective working time of the gearbox are periodically updated and sent to the DMD within a wireless data packet containing also the unique ID of the baler. The simplified block diagram of the ED2 is shown in Fig. 3, where the different components with respect to the ED1 are highlighted.

The same RLC mechanism used for the ED1 has been applied also for the ED2. In this case, the parameter used to define the RLC is the oil temperature of the baler's gearbox. Higher is the temperature and higher is the RLC.

C. *DMD – Data Manager Device*

The first task of the DMD is the estimation of the relative positioning between the tractor and the baler. This critical parameter can be used to improve the pre-crash active safety of the whole machinery and the effectiveness of the stability control algorithm running on the main ECU of the tractor because it takes into account information of the whole machinery. To estimate the relative positioning between tractor and baler the DMD needs to run a complex spatial positioning algorithm based on the one proposed in [12]. It requires the measurements of roll, ϕ_T, pitch, θ_T, and yaw, ψ_T, angles of the tractor plus the roll, ϕ_B, pitch, θ_B, and yaw, ψ_B, angles of the

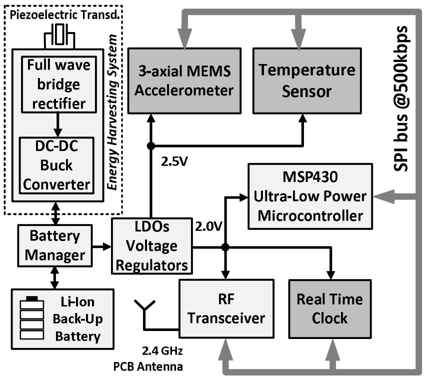

Fig. 3. Simplified block diagram of the implemented ED2

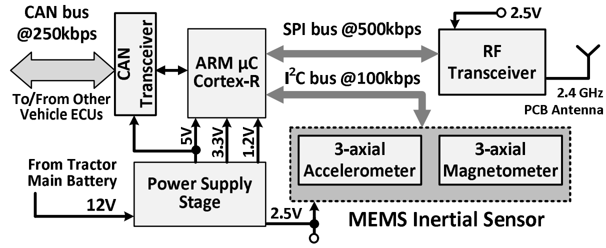

Fig. 4. Simplified block diagram of the impelmented DMD.

baler. The needed relative yaw angle between tractor and baler, ψ_R, can be then easily calculated by the difference between ψ_T and ψ_B. The ϕ_B and θ_B angles are provided directly by the ED1 while all the other angles are calculated by the DMD. In particular the calculation of the yaw angles ψ_T and ψ_B, is a complex time and power consuming task. During the HW-SW partitioning phase of the system design it has be chosen to assign it to the DMD. Indeed, the DMD can exploit a more powerful microcontroller and has not the power consumption constraints of the ED1 because the energy required to its computations is provided by the main battery of the tractor.

The second task of the DMD is the operation as gateway, giving the possibility to share via a classic CAN network the information collected by the EDs with all the other ECUs of the tractor. In particular, the DMD has to provide two kinds of information. The first one concerns the working condition of the baler, and to do this it forwards directly each data packet received from the EDs via CAN. The dedicated tractor ECUs will process the data notifying to the operator if it is time for the programmed maintenance of the baler, or if a high temperature of the oil in the gearbox persists giving a symptom of an imminent malfunction. The second information concerns the data of pitch, roll and yaw angles of both tractor and baler plus the relative yaw angle ψ_R. These data are sent within a dedicated CAN message from the DMD to the main ECU of the tractor where the control stability algorithm runs.

The simplified block diagram of the implemented DMD is shown in Fig. 4. It embeds the same MEMS inertial sensor of ED1 and the same RF transceiver of the EDs. All these components share the same SPI bus. In addition, the DMD has a CAN interface for the data exchange with the other ECU of the tractor. Moreover, it has a completely different power supply stage and all the regulated voltages required for the correct operation of the microcontroller and of the other peripherals are obtained starting from the 12V voltage provided by the main battery of the tractor by means of commercial DC-DC converters.

III. Optimization of the ED's Power Consumption

The optimization of the ED's power consumption plays a key role to obtain autonomous wireless sensor nodes. Applying the classic HW-SW co-design paradigms, the design of an ultra-low power device requires to wisely use each system resource, [13]. For this reason, a task manager has been implemented on both the EDs.

Using data coming from inertial sensors and sensing the amount of energy gathered by the vibrational energy harvester, the task manager allows to optimize the energy budget of the device by means of: i) variation in the sampling and processing data accordingly with the instantaneous RLC (i.e. values of pitch and roll angles for the ED1, and the trend of the oil temperature in the baler gearbox for the ED2); ii) change of the microcontroller (μC) clock frequency with an approach similar to dynamic frequency scaling (DFS) method; iii) turn off the power supply selectively to each peripheral that is not in use for the current task.

A simplified representation of the task manager implemented in both the EDs is shown in Fig. 5. It is very simple and it is comprised of two main states: the *deep sleep* state and the *work* state. Nevertheless its simplicity, it allowed to reduce the power consumption of the two EDs of two orders of magnitude, from few milliwatts down to tens of microwatts when the EDs are in *deep sleep*.

Starting from the *deep sleep* state, the EDs wake up their inertial sensors every $t_{deep\text{-}sleep}$ seconds, and measure the accelerations to which they are subjected. If these are higher than a defined threshold in at least one axis, and for a given number of consecutive samples, then a potential working conditions occurs and the transition from *deep sleep* to *work* happens. Vice versa, the inverse transition in *deep sleep* occurs when in *work* state and the measured accelerations are lower than the threshold for a given number of consecutive samples.

When in *work* state, the EDs acquire and process the data of the parameters that they are monitoring and adjust the sleeping time $t_{sleep\text{-}work}$ in order to adapt the measuring rate according with the estimated RLC of the ED. For the ED1 this is done evaluating the measured pitch and roll angles of the baler. Higher is the RLC and smaller and is the $t_{sleep\text{-}work}$. In the same way, for the ED2, if the trend of the oil temperature in the gearbox is increasing the $t_{sleep\text{-}work}$ is decreased. Of course an higher measuring rate leads to an increase of the average power consumption of the EDs and, if the amount of harvested energy is not sufficient to complete the current task, the battery manager drains the required energy from the Li-Ion battery.

When in *deep sleep* state, instead, the task manager allows to reduce the average power consumption by means of the gradual increase of the interval between two consecutive accelerations measurements, t_{deep_sleep}, depending on the number of consecutive samples measuring acceleration lower

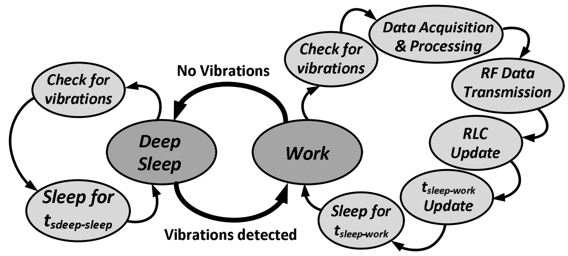

Fig. 5. General framework of the task manager implemented in both the EDs.

than the defined thresholds. Higher is this number and larger is t_{deep_sleep}, up to a maximum of 2 minutes in order to keep a good reactivity after long periods of inactivity of the ED.

IV. Experimental Measurements

A preliminary characterization of the natural frequencies of vibration occurring in the baler when on duty has been carried out by means of a LabView-based data acquisition system. It consists of a high performance 3-axial accelerometer from PCB Piezotronics connected to a NI-cRIO-9233 acquisition board and a NI-USB9162 high speed USB carrier from National Instruments. Post processing elaborations of the accelerations measured in different places on the baler shown that the higher vibrations occurred in the range 0.2g ÷ 1.1g at the frequency of 112Hz imposed by the conversion ratio of the gearbox of the baler. Consequently 112Hz has been chosen as frequency to which tune the resonance frequency of the piezoelectric transducer used. It has a cantilever beam shape with two active piezoelectric layers on both its surfaces. Each layer has its own two output terminals and gives its independent contribution in terms of output voltage and output current. Consequently, it is possible to choice if connect the output terminals of the two layers in series or in parallel resulting in a larger output voltage (series) or a larger output current (parallel), depending on the requirements of the specific application.

The transducer has been characterized in laboratory for both the series and parallel configurations, using an ad-hoc setup based on an electromagnetic shaker (i.e. K2007E01 from Modal Shop inc.) for controlled generation in frequency and amplitude of the vibrations (0.3g, 0.5g and 1g in our case). The tuning at 112Hz has been obtained fixing a tip mass of 1gr to the free end of the transducer (which helps also the power generation inducing a larger deformation of the transducer for a given stimulus) and adjusting the transducer's clamping point.

Fig. 6 shows the obtained open circuit output voltages, V_{OUT}, as function of the frequency of the vibrational stimulus with stimuli reproducing vibrations in the range of the real ones occurring on the baler. Fig. 7, instead, shows the output power, P_{OUT}, delivered by the transducer to a variable resistive load, R_{Load}, under the same testing conditions at the desired resonance frequency. It is possible to note as the type of connection of the active layers of the transducer affects only the generated output voltage, V_{OUT}, as shown in Fig. 6. While, as expected, it does not affect P_{OUT}, that depends only on the amplitude of the stimulus. Indeed, the two graphs of Fig. 7 show that the peak value of P_{OUT} is approximately the same but, of course, it occurs for different load conditions because

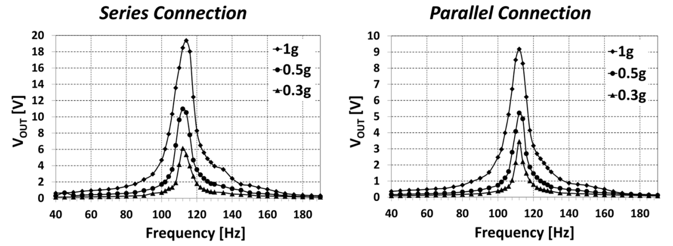

Fig. 6. Measured output voltage vs the frequency of the stimulus for both series and parallel connections of the active layers of the V22B transducer.

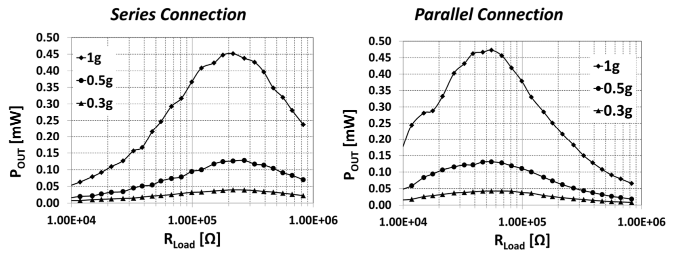

Fig. 7. Measured output power vs. output load R_{Load} for both series and parallel connection of the active layers of the V22B piezoelectric transducer.

the change of configuration modifies the effective output capacitance of the transducer and consequently its output impedance.

Moreover, the average power consumption of ED1 and ED2 has been measured in both *deep sleep* and *work* state for different acquisition rate (i.e. RLC) in order to evaluate the impact of this parameter on the overall power consumption and the self-sustainability of the devices. The measurements were carried out by means of a N6784A battery drain module integrated into N6705B DC power analyzer from Agilent Technologies with dedicated 14585A Analysis Software. The most relevant results are reported in TABLE I. and TABLE II.

The percentage of self-sustainability of the EDs, when in *work* state (i.e. the only state where the energy harvester is on duty) and for the different working conditions, can be obtained combining the results shown in Fig. 7 with TABLE II. In particular, in conditions of matched load and vibrations of 1g, the realized energy harvesting system is able to fully sustain the ED1 up to "low" RLC, while it provides 86%, 26% and 14% of the energy required by the ED1 in "medium", "high" and "very high" RLC, respectively. This is due to its tasks which are more time and power consuming compared to the tasks of the ED2 when in *work* state. Indeed, in the same working conditions, the energy harvester is able to fully sustain the ED2 for every RLC.

V. CONLCUSIONS

The paper shown as the combination of two enabling technologies like energy harvesting systems and wireless sensor nodes allows to obtain devices potentially autonomous. This contributes to the use of such devices in application fields like agriculture where, up today, it was very difficult to introduce functionalities able to enhance the active safety for both machinery and operator, due to the absence of electronics on board in most of the implements and trailers.

TABLE I. AVERAGE POWER CONSUMPTION OF ED1 AND ED2 WHEN IN *DEEP SLEEP* STATE AND MEASURED FOR DIFFERENT $T_{DEEP\text{-}SLEEP}$ INTERVALS

Average Power Consumption [µW]		
$t_{deep\text{-}sleep}$ *[sec]*	***ED1***	***ED2***
5	80	133
30	23	32
120	15	17

TABLE II. AVERAGE POWER CONSUMPTION OF ED1 AND ED2 WHEN IN *WORK* STATE AND MEASURED FOR DIFFERENT RISK LEVEL CONDITIONS

Average Power Consumption [µW]			
RLC	$t_{sleep\text{-}work}$ *[sec]*	***ED1***	***ED2***
Very Low	120	156	28
Low	60	284	45
Medium	30	526	77
High	10	1729	208
Very High	5	3125	404

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